Interior Permanent Magnet Machine For Use In The XM1124 Hybrid Electric HMMWV

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Report Documentation Page			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **11 AUG 2009**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Interior Permanent Magnet Maching For Use In The XM1124 Hybrid Electric HMMWV**		5a. CONTRACT NUMBER **DAAE07-02-C-L065** 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Justin Owen; Mike Marcel**		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **DRS Test and Energy Management, LLC. Huntsville, AL**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA**		10. SPONSOR/MONITOR'S ACRONYM(S) **TACOM/TARDEC/RDECOM** 11. SPONSOR/MONITOR'S REPORT NUMBER(S) **20154**
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**16**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Introduction

- DRS-TEM was tasked in the Control Development, Testing, and Validation of a Prototype IPM suitable for use in the XM1124 HMMWV
  - IPM chosen due to special characteristics that make it desirable when compared to other ac machines (Specifically, SPM Machines)
    - Rotor design topology produces increased saliency ratio (Armature Axis Inductance is larger than the Field Inductance)
    - Saliency makes the reluctance torque component available, in addition to the permanent magnet torque, for low speed torque boost as well as extended-speed operation under FW Control
    - Trajectory Control implemented in order to utilize unique machine characteristics and optimize performance

IPM Machine Modeling

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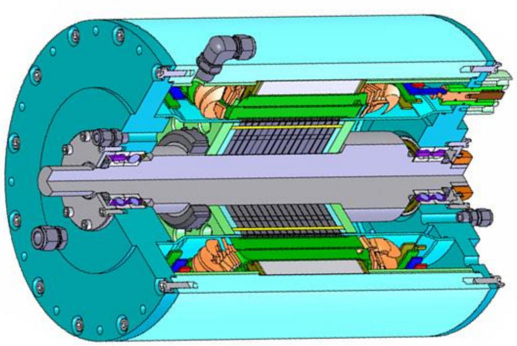
Table 1 : XM1124 Prototype IPM Motor Parameters

Number of pole pairs – P	4
Stator resistance – R	9.9e-3 Ω
Magnet flux linkage – λ_f	0.098 Wb
d-axis inductance – L_d	400e-6 H
q-axis inductance – L_q	800e-6 H
Maximum phase voltage – V_{sm}	230 V_{pk}
Maximum dc-link voltage – $V_{dc\text{-}link}$	400 V_{dc}
Maximum phase current – I_{sm}	600 A_{pk}
Base Speed – ω_b	1500 RPM
Crossover Speed – ω_c	5600 RPM
Rated Power – P_R	100 kW



IPM Governing Equations:

Voltage in the d-q rotating reference frame

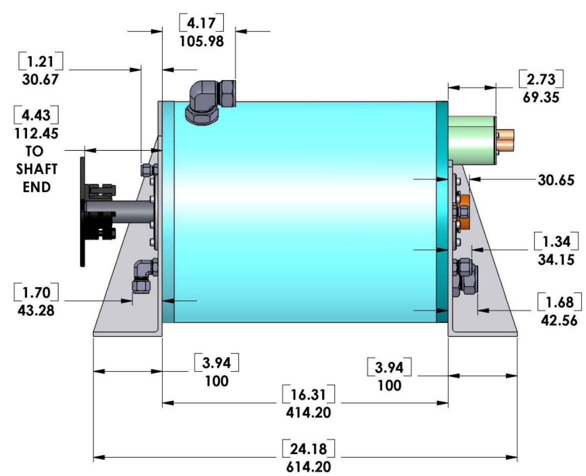
$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -\omega_e L_q \\ \omega_e L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e \lambda_f \end{bmatrix}$$

Torque Developed

$$T = \frac{3}{2} P \left[\lambda_f i_q + \left(L_d - L_q \right) i_d i_q \right]$$

Permanent Magnet Component

Synchronous Reluctance Component



- For successful control implementation, operating limits and stability criteria must be effectively defined and observed
- Current and voltage restraints are used in order to define the operating region for the Maximum Torque Per Amp (MTPA) Trajectory

Current Limit Circle

$$X^2 + Y^2 = r^2$$

Center Point Lying at zero with a radius of I_{sm}

Voltage Limit Ellipses

$$\frac{(X-h)^2}{a^2} + \frac{(Y-k)^2}{b^2} = 1$$

Center Point Lying at

$$(h,k) = \left(0, \frac{-\lambda_f}{L_d}\right)$$

Half Length of Major Axis

$$a = \left(\frac{V_{om}}{\omega_e * L_d}\right)$$

Half Length of Minor Axis

$$b = \left(\frac{V_{om}}{\omega_e * L_q}\right)$$

Where $V_{om} = V_{sm} - I_{sm} * R$ and $V_{sm} = \frac{V_{dc-link}}{\sqrt{3}}$

IPM Machine Modeling

- The MTPA Trajectory utilizes machine characteristics and system limitations in such a way as to maximize the torque/amp ratio while maintaining optimum efficiency.
- Intersecting point of MTPA Trajectory and current limit circle yields maximum operating point at base speed
  - Base Speed is defined as the speed at which the load generated CEMF reaches the inverter bus voltage

MTPA Trajectory
Maximum Operating Point
At Base Speed

$$i_{dA} = \frac{\lambda_f}{4(L_q - L_d)} - \sqrt{\frac{\lambda_f^{\,2}}{16(L_q - L_d)^2} + \frac{I_{sm}^{\,2}}{2}}$$

$$i_{qA} = \sqrt{I_{sm}^{\,2} - i_{dA}^{\,2}}$$

Analytical Maximum Operating Point $(i_{dA}, i_{qA}) = (-367A, 474A)$

Operational MTPA Trajectory
d-axis current calculation

$$i_d^{\,*} = \frac{\lambda_f}{2(L_q - L_d)} - \sqrt{\frac{\lambda_f^{\,2}}{4(L_q - L_d)^2} + \left(i_q^{\,*}\right)^2}$$

d-axis Current command calculated based on q-axis current command (Indirect Torque Control, Speed Control Error)

Modeling and Simulation between Base Speed and Crossover Speed

- In order to safely operate the IPM beyond base speed and up to crossover speed, the controlling algorithm must be transitioned to MTPA + FW Control
  - Crossover speed is defined as the speed at which the no load PM generated EMF reaches the bus voltage
  - Beyond base speed, MTPA or FW control is selected based on the load condition
  - Required d-axis current is calculated using q-axis current command and FW equation
  - Great care must be taken to avoid stability criteria due to a non-real i_d calculation

FW Control d-axis Current Calculation

$$i_d^* = \frac{-\lambda_f}{L_d} + \frac{1}{L_d}\sqrt{\frac{V_{om}^2}{\omega_e^2} - \left(L_q i_q^*\right)^2}$$

Only Real while

$$\left|i_q^*\right| \leq \frac{V_{om}}{\omega_e L_q}$$

If non-real solution

$$i_d^* = \frac{-\lambda_f}{L_d}$$

MTPA Trajectory

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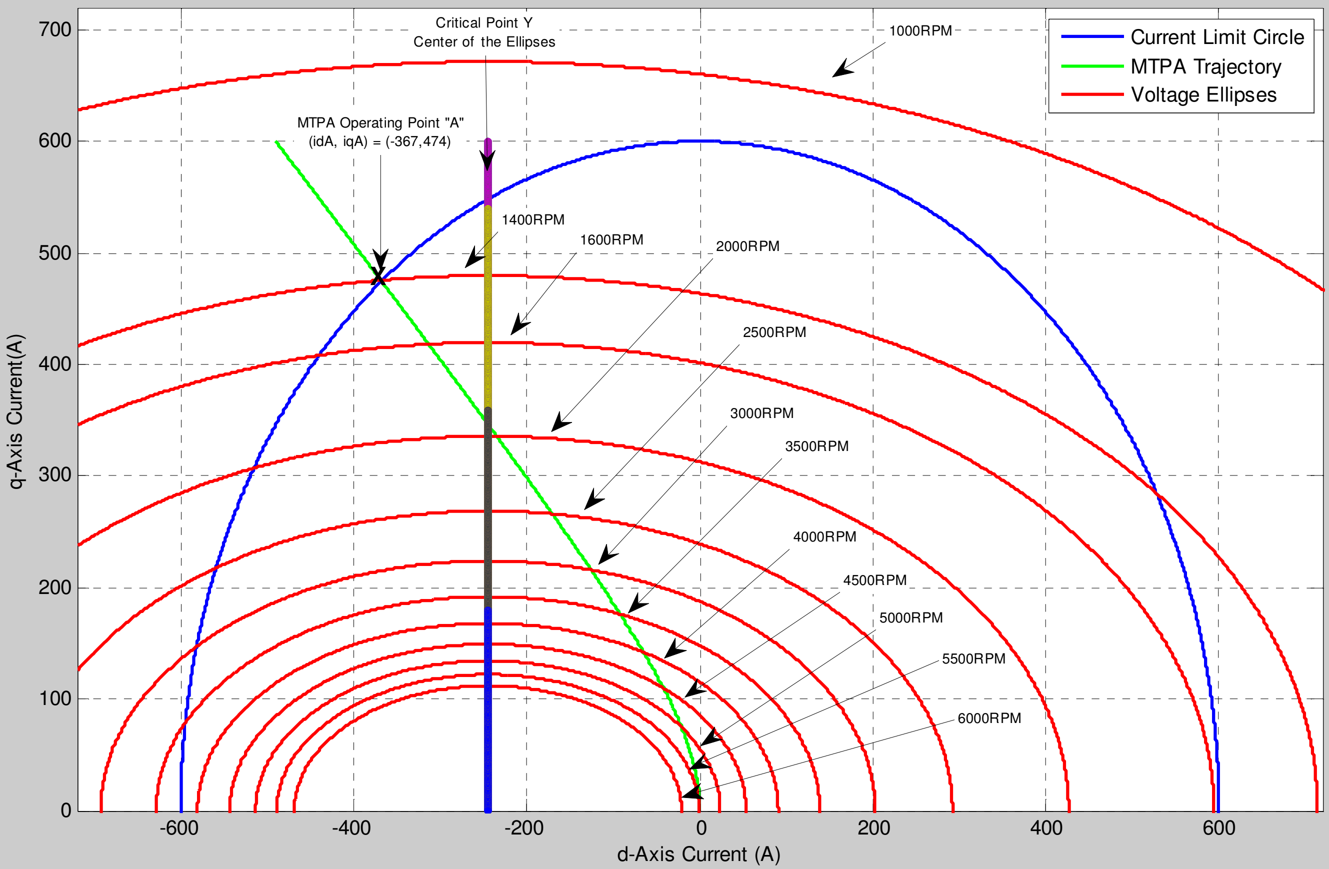
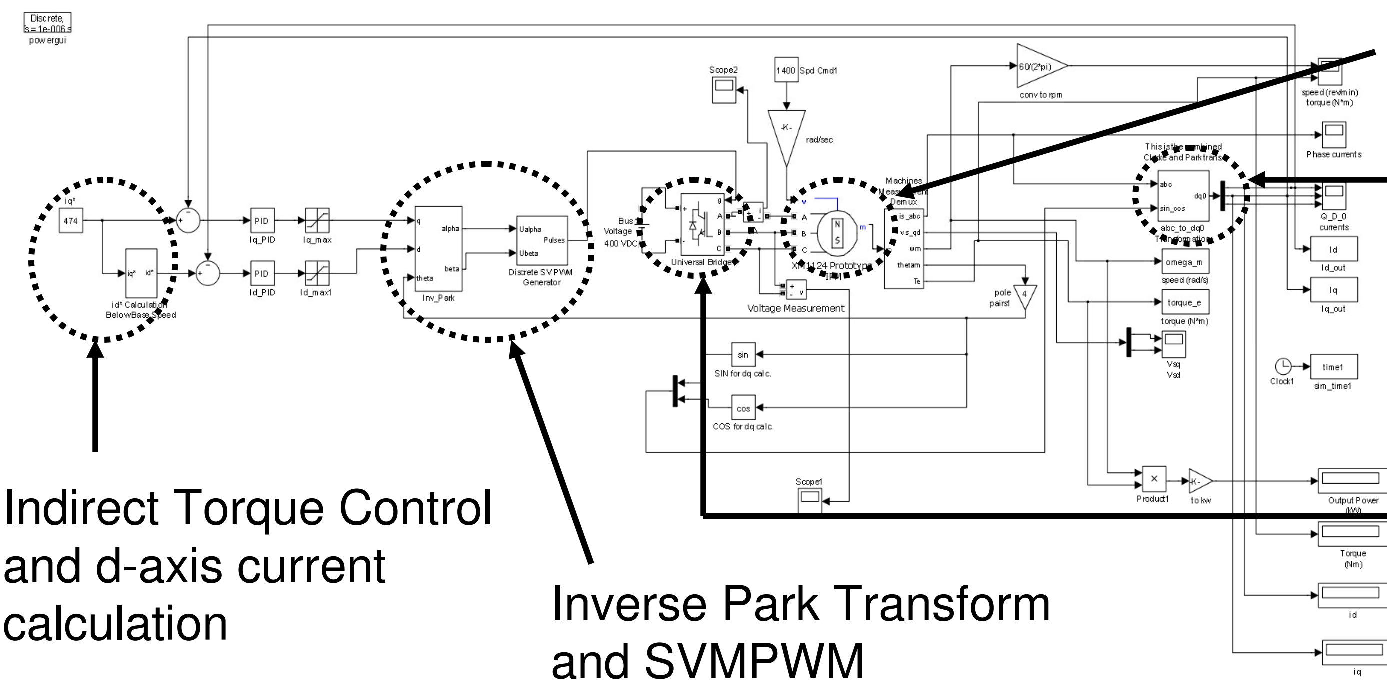
Current Limit Circle, Voltage Limit Ellipses, and MTPA Trajectory for The XM1124 Prototype IPM in the i_d-i_q Plane



Modeling and Simulation Below Base Speed

- MATLAB® Simulink used to model IPM machine and controlling algorithm



XM1124 Prototype IPM Model

abc to dq Transform (Clarke and Park)

Indirect Torque Control and d-axis current calculation

Inverse Park Transform and SVMPWM

3-Phase Inverter

Simulated Results

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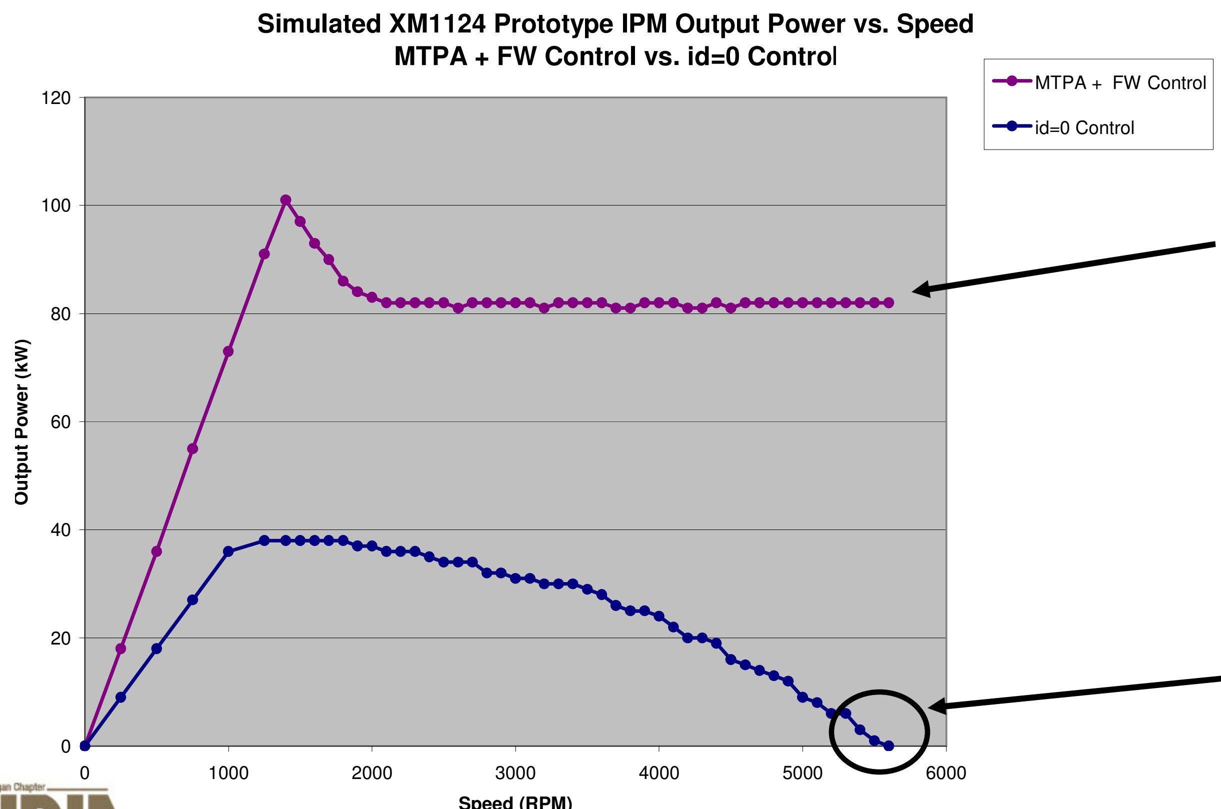
- Simulated Comparison of SPM machine and Id=0 Control



MTPA is stable below base speed and FW Control performs well in the CPR

Crossover Speed Observed

Simulated IPM Torque Comparison

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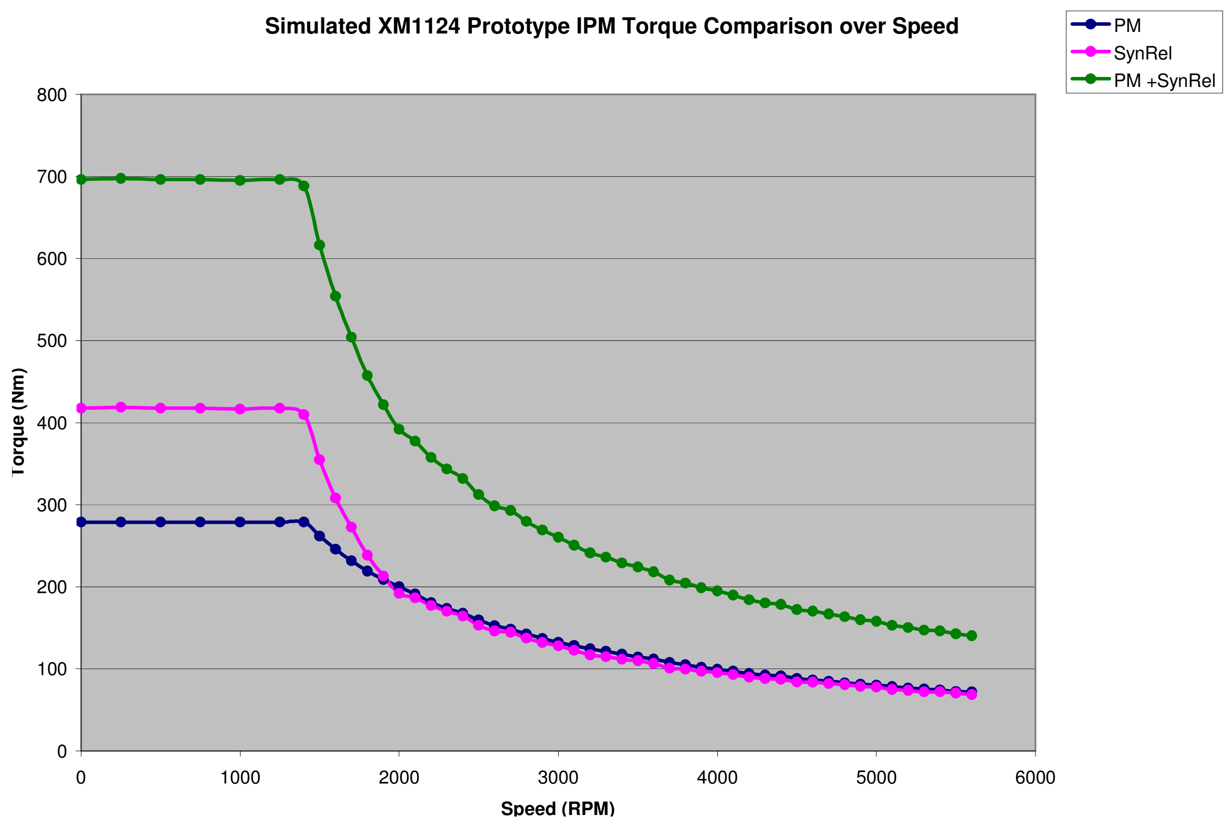
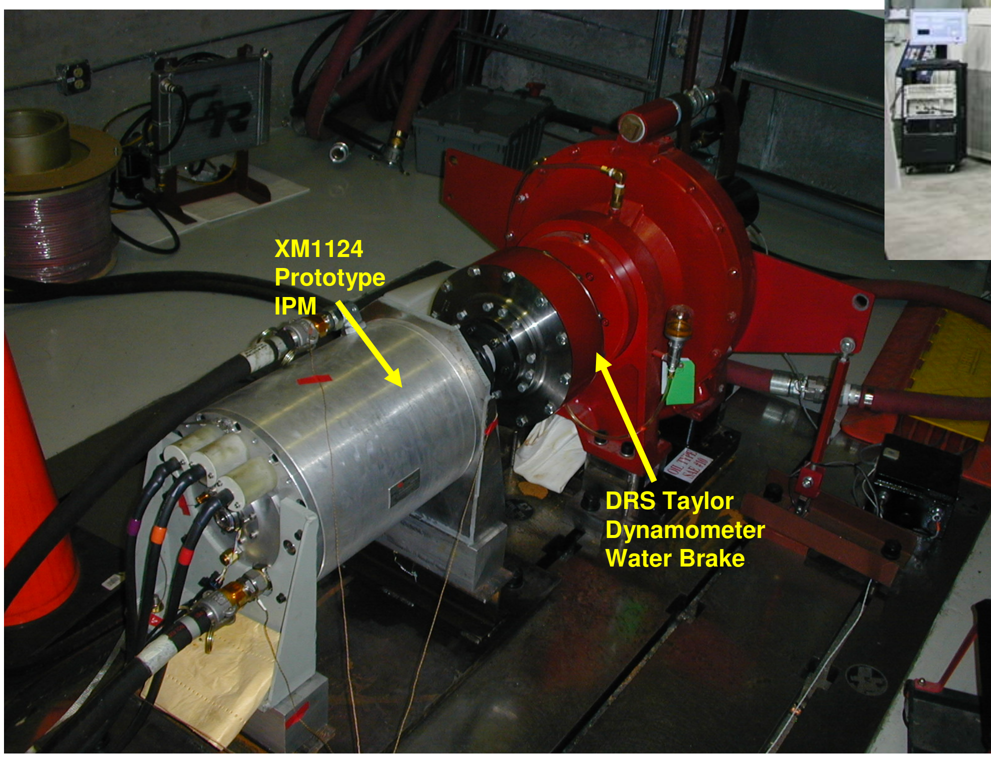
- Extraction of individual torque components is very beneficial
- Sum of torque components is greater than either alone



Experimental Validation

- DRS System Integration Lab (SIL) used to test machine and controlling algorithm



- XM1124 Prototype IPM coupled directly to DRS Taylor Dynamometer Water Brake for load testing

Saturation Effects

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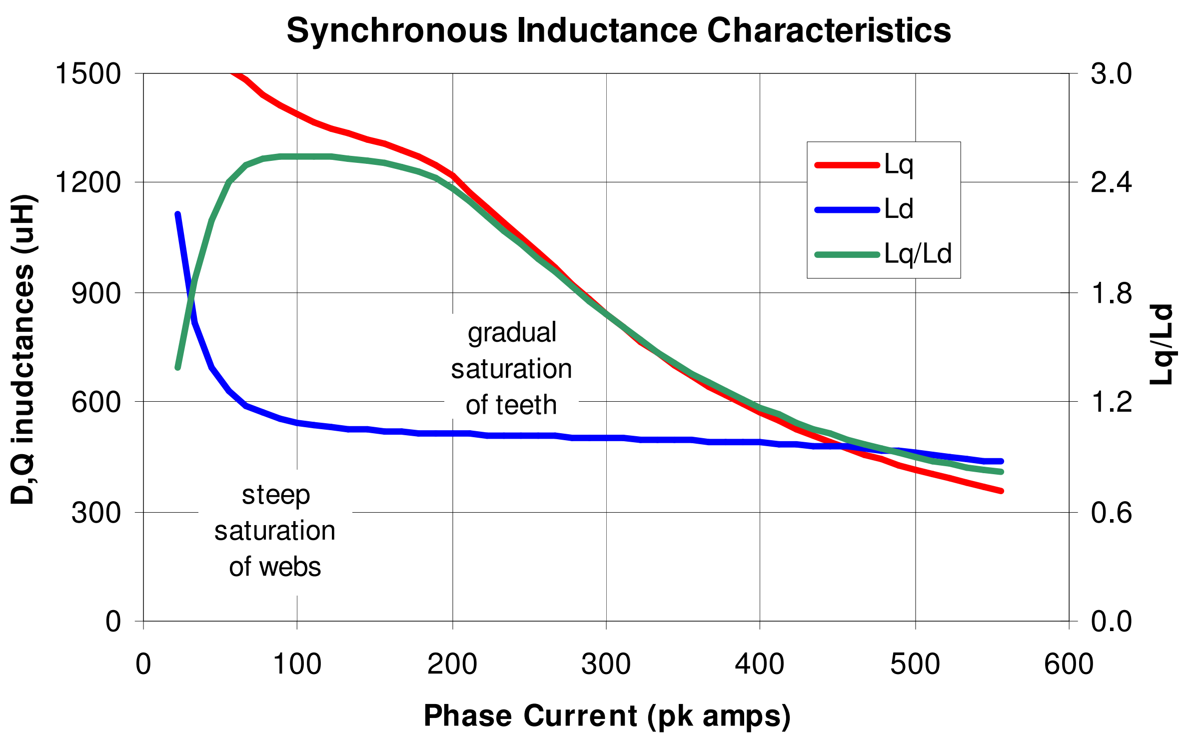
- Significant saturation of the armature axis inductance observed at start of experimental testing
- Results in reduction of saliency ratio and limits overall output torque by reduction of synchronous reluctance torque component



Experimental Results with Saturation Effects

- Prototype IPM tested and controlled by DRS MCU using Trajectory Control
  - MCU introduces safety limitations not observed in initial simulation
    - Reduced DC-Link Voltage
    - Current Safety Margin for IGBT's
- Water Brake provided desired torque load while MCU controlled IPM in speed control mode
- Approximately 300 Nm of torque observed while using MTPA below base speed.
  - Torque reduction attributed to quadrature axis saturation at higher currents negating benefits of synchronous reluctance component

Experimental Results with Saturation Effects

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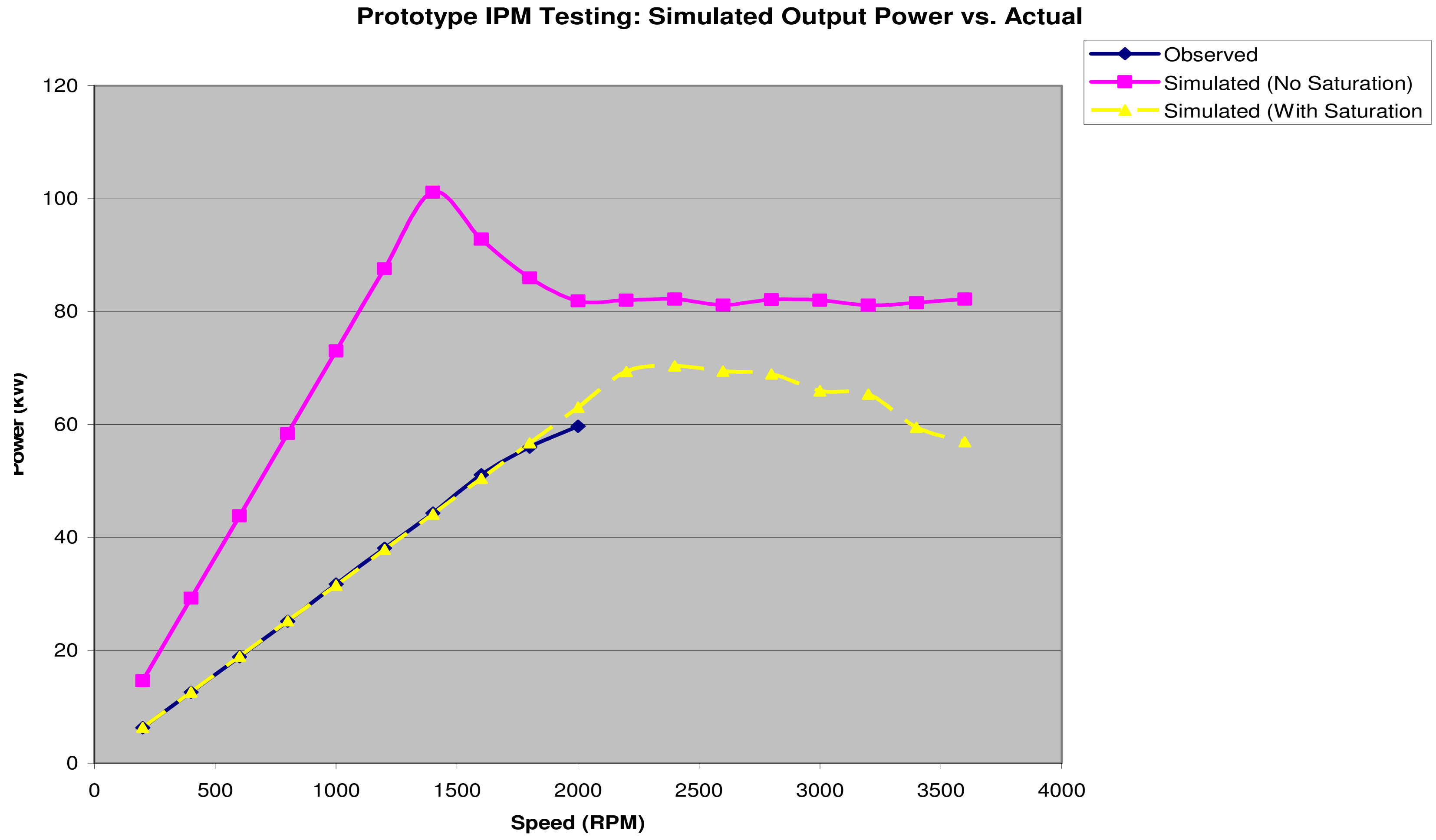

Conclusions

- Modeling and Simulation of XM1124 Prototype IPM show the distinct advantages of this new technology
- Unique motor characteristics produce advantages not seen in other ac machines (SPM in general)
- Actual testing revealed IPM torque output heavily dependent on quadrature axis inductance saturation
- Torque boost at lower current levels due to additional synchronous reluctance component is apparent
- Testing is ongoing
  - Motor power efficiency mapping
  - FW Control
  - Comparison with similar SPM traction machines

Acknowledgements/Contact

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DRS-TEM would like to thank TARDEC for their continued support in the XM1124 program!

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